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Twenty Meter Space Telescope Based on Diffractive Fresnel Lens

J. Early, R. Hyde, R. Baron

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Twenty meter space telescope based on diffractive Fresnel lens

[a]Jim Early, [a]Rod Hyde and [b]Richard Baron
[a]Lawrence Livermore National Laboratory, PO Box 808, Livermore, CA 94550
[b]JPL, 4800 Oak Grove Drive (M/S: 301-486), Pasadena, CA 91109-8099

ABSTRACT

Diffractive lenses offer two potential advantages for very large aperture space telescopes; very loose surface-figure tolerances and physical implementation as thin, flat optical elements. In order to actually realize these advantages one must be able to build large diffractive lenses with adequate optical precision and also to compactly stow the lens for launch and then fully deploy it in space. We will discuss the recent fabrication and assembly demonstration of a 5m glass diffractive Fresnel lens at LLNL. Optical performance data from smaller full telescopes with diffractive lens and corrective optics show diffraction limited performance with broad bandwidths. A systems design for a 20m space telescope will be presented. The primary optic can be rolled to fit inside of the standard fairings of the Delta IV vehicle. This configuration has a simple deployment and requires no orbital assembly. A twenty meter visible telescope could have a significant impact in conventional astronomy with eight times the resolution of Hubble and over sixty times the light gathering capacity. If the light scattering is made acceptable, this telescope could also be used in the search for terrestrial planets.

1. INTRODUCTION

There have been extensive efforts to find technologies that allow scaling of space telescopes beyond the two meter scale of Hubble. The two traditional strategies have been to make conventional monolithic optics lighter or to use membrane surfaces with adaptive optics. The concept of using Fresnel optics as part of power beaming, astronomy or sail systems has been suggested by several authors[1,2]. The primary issues for large Fresnel optics are the difficulties in fabricating these structures and deploying them in space and for astronomy missions the extremely narrow frequency range of these optics. In proposals where the telescope is used to transmit narrow frequency laser power[1], the narrow bandwidth has not been an issue. In applications where the optic is to be used as part of a telescope, only around 10^{-5} to 10^{-6} of the optical energy in a narrow frequency band can be focused into an image.

This article will briefly summarize the theory of Fresnel optics and address the fabrication of very large space optical systems with Fresnel lenses. The limited frequency response of a Fresnel optic is addressed by the use of a corrective optic that will broaden the frequency response of the telescope by three or four orders of magnitude. This broadening will dramatically increase the optical power capabilities of the system and will allow spectroscopy studies over a limited range. Both the fabrication of Fresnel optics as large as five meters and the use of corrector optics for telescopes have been demonstrated at LLNL[3,4]. Folded optics designed to allow scaling to much larger sizes have been investigated, and good optical performance has been demonstrated on subscale optics. The use of Fresnel amplitude zone plates made of very thin opaque material for solar and laser sail missions is also discussed.

For initial deployment a lens with no folding and a simple space deployment procedure is desirable. Twenty meters is the largest lens diameter that can be rolled and fitted in a Delta IV launcher using its largest payload shroud. The design of the telescope and its potential performance will be discussed.

2. TRANSMISSIVE FRESNEL OPTICS

2.1 Transmissive optics

A key feature of this concept will be the use of a thin transmissive primary optic in the telescope design. The problem with membrane mirrors, of course, is that it is hard to control their shape to the $\lambda/20$ scale precision needed to attain $\lambda/10$ optical tolerances. The source of this difficultly is that mirrors reflect light, thereby doubling the effect of surface errors. In contrast, path-length errors caused by surface distortion of a thin, uniform thickness transmissive film are canceled (not reinforced) as light arrives at and then departs from the surface. In actual lenses, this path-length cancellation is not perfect because the incoming and outgoing rays are not traveling in quite the same directions. If the light is bent through angle θ, then the path-length error in a mirror is amplified by a factor (1 + cosθ), whereas that in a thin lens is reduced by (1-cosθ). Thus lenses have a (1+cosθ)/(1-cosθ) advantage over mirrors. By making the lens weak, i.e., by keeping θ small, this tolerance gain becomes huge. In a very slow lens (f/100) visible-light tolerances increase up to nearly a centimeter, a tremendous practical advantage when trying to field a thin optical-quality membrane optic in space.

2.2 Diffractive optics theory

The classic circular Fresnel pattern for an amplitude zone plate is illustrated in Fig. 1. For a phase plate the glass surface local slope results in a 2π phase shift in each zone with a 2π step at the zone edge. Just as with standard optics a point focus can also be formed with orthogonal cylindrical lenses (Figures 2).

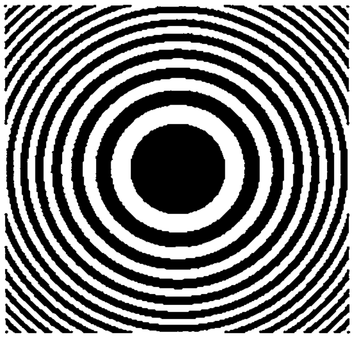
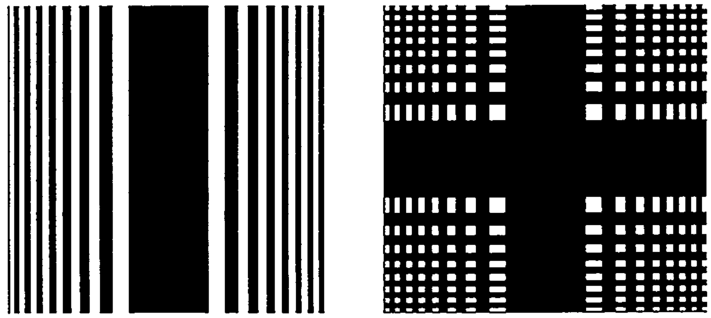


Fig. 1: Circular Zone Plate



a. b.

Fig. 2: Linear zone plate; a) line focus
b) point focus with orthogonal lines

The total number of zones, N, are given by:

$$N = D^2/8\lambda F = D/8\lambda f_{number} \quad (1)$$

Where λ, D and F are the wavelength, optic diameter and optic focal length respectively. The width of the outer zone (the smallest zone) is $2\lambda f_{number}$. When the f_{number} (F/D) is very large, then these features become easy to fabricate using optical lithography technology.

Even with a normal lens the light distribution in the focal plane depends on the wavelength. For example the diameter of the central Airey spot, d, is proportional to the wavelength.

$$d = (2.4F/D)\lambda \quad (2)$$

In a broadband image the short wavelength light has a higher resolution. However all the wavelengths have the same focal plane for zero dispersion optics.

For a Fresnel optic the focal length also will depend on the wavelength

$$F = (D^2/8N)(1/\lambda) \quad (3)$$

and will severely limit the useful bandwidth, Δλ,of a telescope. For good images:

$$\Delta\lambda/\lambda < 1/8N = f_{number}\,\lambda/D \quad (4)$$

If the f_{number} of the telescope is 100 and the diameter is 20m, then for 1μm light $\Delta\lambda/\lambda = 5\times10^{-6}$.

Unless the telescope features extraordinarily large f-numbers, the diffractive Fresnel primary optics will be inherently micro-bandwidth optical elements. The bandwidth may be acceptable for laser communications or power beaming, but it is a major limitation for an imaging system. For an imaging system we must achieve higher optical bandwidth by the use of chromatic correction optics.

In the next section we discuss how to correct for this chromatic aberration associated with Fresnel optics. The intensity distribution in the focal plane will also be different for different types of Fresnel lens, i.e. phase plates, zone plates, circular plate and orthogonal plates. We will not attempt to change these amplitude distributions in the focal plane nor the wavelength pattern variation found in standard optics. It is essential to note that the chromatic corrections will address only the variation in focal length for the Fresnel lens.

One consequence of using a large f_{number} lens with a large diameter is that the focal length will be very large. For a f_{100} lens with a 20m diameter, the focal length is two kilometers. The primary optic, referred to as the Magnifying Glass, will have to be a separate spacecraft from the spacecraft, referred to as the Eyepiece, containing the remainder of the optical train.

2.3 Corrector plate for wavelength aberrations

To achieve high-precision chromatic correction for the zone plate, we try to cancel its chromatic aberrations with correcting optics in the optical train of the telescope. A technique was invented 100 years ago by Schupmann[5] who showed that any chromatic dispersion introduced at one optical element could be canceled by placing a second, inverse-power element with the same dispersion at an image site of the original element. The corrector optic's effectiveness will depend on its size, but increasing the bandwidth of the telescope by four orders of magnitude should be possible.

Physically, the reason Schupmann correction works for a diffractive telescope is clear (figure 3); light leaves each point of the Magnifying Glass's diffractive lens in an angular spray, each color being sent into a different direction. As the light from this site travels towards the Eyepiece it spreads apart, diverging both spectrally and physically; both effects must be corrected. The physical reassembly is achieved first, by making the light pass through a reimaging telescope as it enters the Eyepiece. This internal telescope focuses the surface of the Magnifying Glass onto that of the Fresnel Corrector, thereby physically recombining rays which left each site on the first diffractive lens to a matching site on the second one. Now each site on the Fresnel Corrector sees an incoming angular/color spray corresponding to that from the departure site on the Magnifying Glass; by employing an inverse (defocusing) diffractive profile, it can remove this angular/color spray. As a result, each ray bundle is now both physically and spectrally recombined; the set of bundles can then be brought to a common achromatic focus.

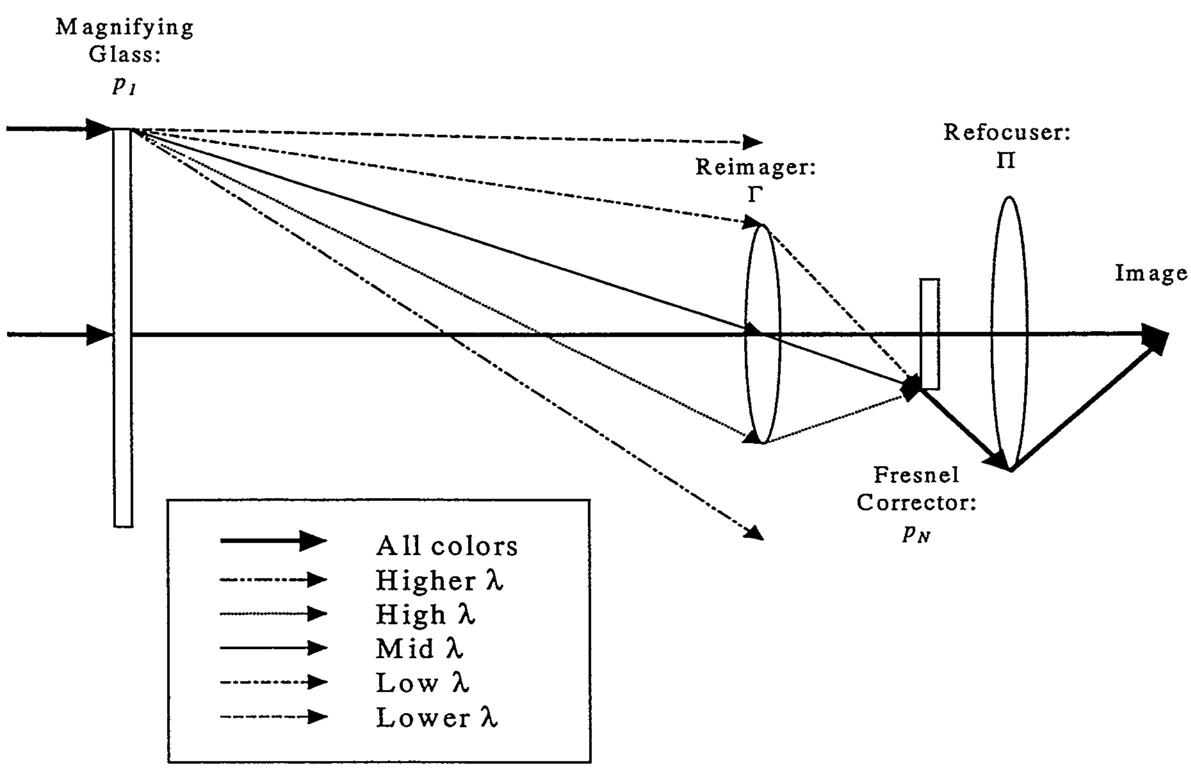


Figure 3 – Optical paths of different colors through Fresnel telescope

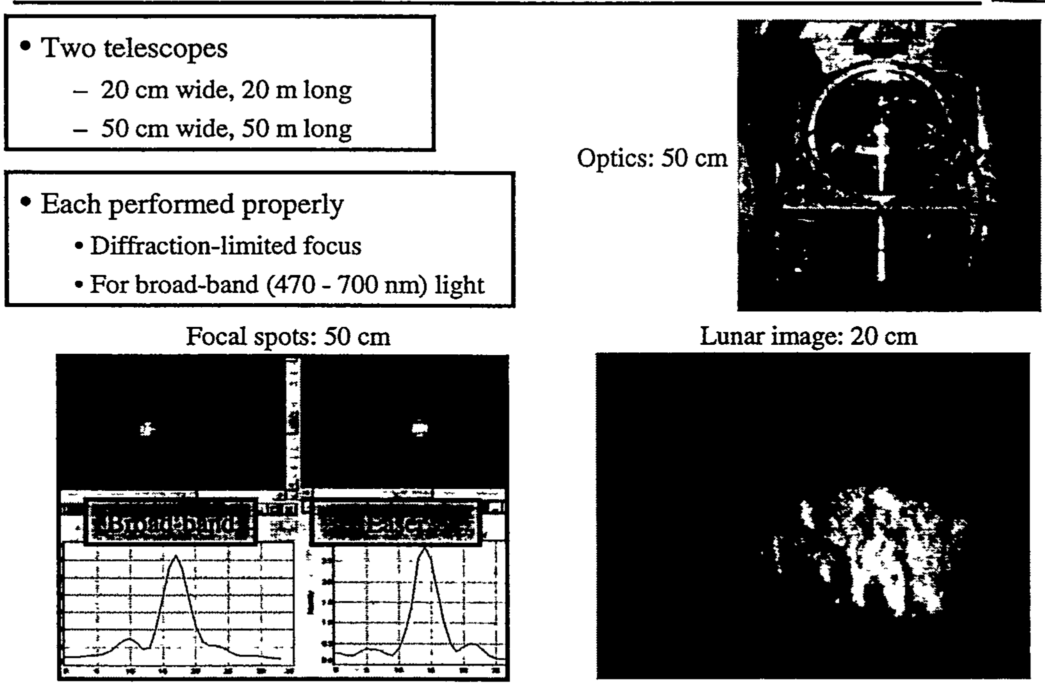
The details of the design and performance of the corrector optic can be found in references 3 and 4.

3. LENS FABRICATION AND DEMONSTRATIONS AT LLNL

LLNL has also addressed the issue of fabrication of large meter scale optics utilizing techniques that can be scaled to much larger sizes. At LLNL we have facilities that were built for fabrication of meter scale diffractive optics that are needed for the new laser fusion laboratory currently under construction. We now have facilities, techniques and experienced personnel needed to produce very large (up to one meter in a single piece) diffractive optics in large numbers for use as diffraction gratings, Fresnel phase plate lenses or optical control elements. We have also addressed issues of joining meter sized optics together to fabricate much large optical structures. This basic capability can now be used to address the issues of design and fabrication of Fresnel phase plate optics in glass or plastic and amplitude zone plates in sail materials.

At LLNL we have fabricated Fresnel phase plates at diameters of 20 and 50cm. Using a corrector plate fabricated by JPL, we have demonstrated that the chromatic aberrations can be corrected in telescope configurations and that diffraction limited images can be formed with broadband ($\Delta\lambda/\lambda \sim 0.1$) light (figure 4). Both phase plates and amplitude plates have the same wavelength dependence in their chromatic aberrations, and broadband performance has been demonstrated with both types of optics. For IR and UV missions there may not be glasses that are transmissive. For these missions an amplitude zone plate design made from opaque material may be necessary despite the optical efficiency that is only 10% of a phase plate design.

Figure 4- Broad-band Diffractive Telescopes



To scale this technology to very large optics meter sized optical sections are made with current techniques and joined to form a large optic. The joints must be designed to function in the space environment and to maintain the required optical position tolerances. Figure 5 shows a 5m foldable Fresnel lens recently fabricated at LLNL. Most of the structure seen in this figure is bracing required to protect the lens from wind loads in this open air demonstration. The 5m foldable optic was too large to test indoors, but an 80cm optic that consisted of six panels connected by hinged joints did show diffraction limited performance (Fig.6). The 80 cm optic showed the same performance before and after being folded.

Fig.5: 5 m Fresnel lens made with 700mm glass

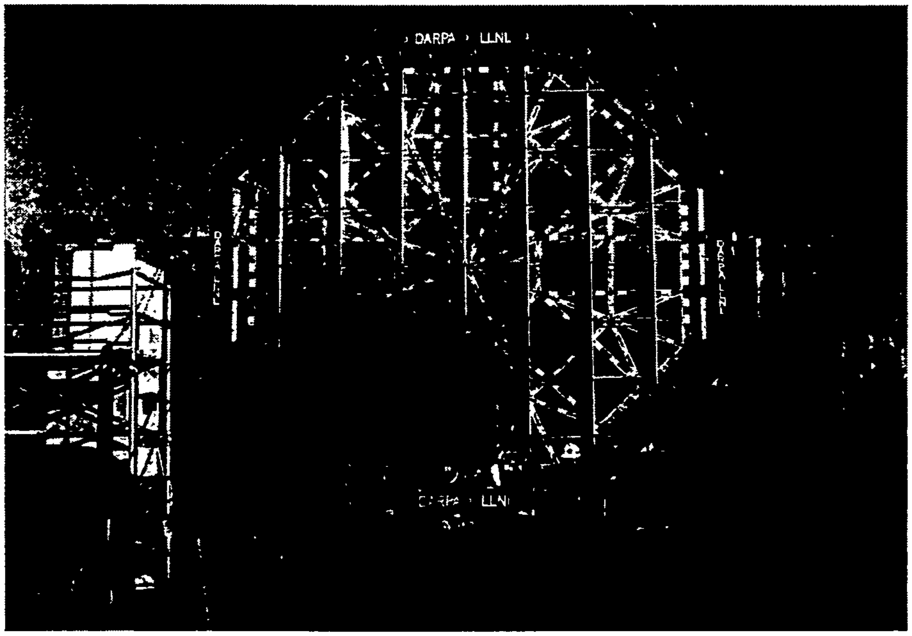
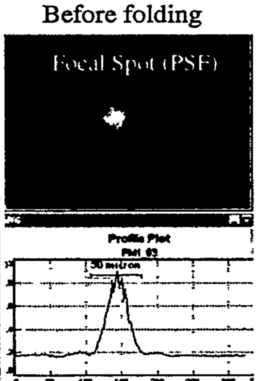


Fig. 6: Thin, Foldable, Six-Panel Diffractive Lens

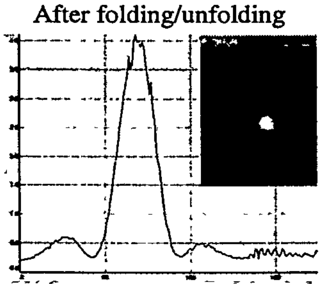
- Lens specifications
  - 75 cm aperture, 1 mm thick silica
  - 39 meter focal length (f/52) @ 532 nm
  - Six panels, joined via thin (1.5 mil) Ti tabs

Optical performance

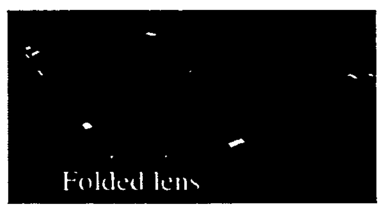
Before folding



After folding/unfolding



Focal spots are nearly the same size in the two cases



4. 20m SPACE TELESCOPE

4.1 Space deployment

For an f_{number} 100 optic the outer (thinnest) ring is around 100μm for a visible optic. Fabricating the rings to a fraction of this dimension with standard optical lithography has been demonstrated with the LLNL equipment. Holding this in-plane precision in a deployed optic will depend on the material properties and the thermal control of the optic. If the optic is held at uniform temperature, then the only impact of a change in temperature is an easily corrected change in focus[4]. Uniform temperature can be achieved by having a uniform solar illumination of the optic. For non-shaded optics the optic will be bare with no structures to cast shadows on the optic.

The optic can be held flat by spinning (the preferred method) or by applying radial tension at the circumference with external structures. For transmissive optics the out of plane optical tolerances are large and easily achieved. The stresses must however be distributed without causing local in-plane distortions in the optic.

Thin glass optics are flexible enough to be rolled into configurations that can fit into the payload volumes of current launchers. Circular primary optics of 9m can fit in the Delta III fairing and of 20m can fit in the Delta IV. For a larger primary the optics must be folded in origami patterns (figure 5) or fan folded and rolled. Fig.7 shows the flexibility of thin glass sheet. Rolling the lens for packaging in the launch shroud will not cause stress problems, but the lens will have to be clamped in a protective case that spreads the supporting stresses over large areas to protect against launch vibrational stress. This is basically the same technique that is used to routinely ship this thin glass through the mail. Fig.8 illustrates the packaging arrangement of the Fresnel lens and separate Eyepiece spacecraft relative to a Delta IV shroud envelope.

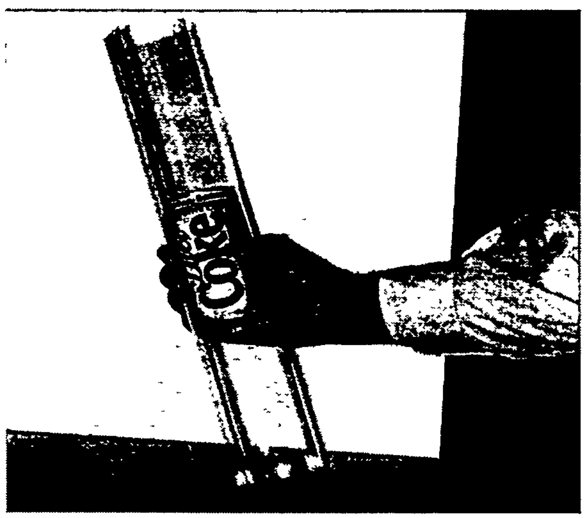


Fig 7: 50μm commercial glass sheet is very flexible

4.2 Spacecraft specifications and performance

A 20m telescope based on Fresnel optics could be packaged in a Delta IV and deployed in geostationary or higher orbits such as an Earth trailing orbit. Such a telescope would provide eight times the resolution and sixty-four times the light gathering capacity of the Hubble telescope. This telescope could observe weather details on Mars with 10km resolution and on Saturn with 100km resolution. It could provide 1AU resolution of planetary accretion disks or planetary nebula out to 600 light years. If the light scattering properties are acceptable, then this telescope design could also be used for extra-solar planet finding missions[6].

Table 1 gives the mass budget for the spacecraft. The 20m Fresnel lens is made from 100μm glass sheet. This thickness is readily available and is a reasonable extrapolation from lens thicknesses that have been fabricated at LLNL. The lens

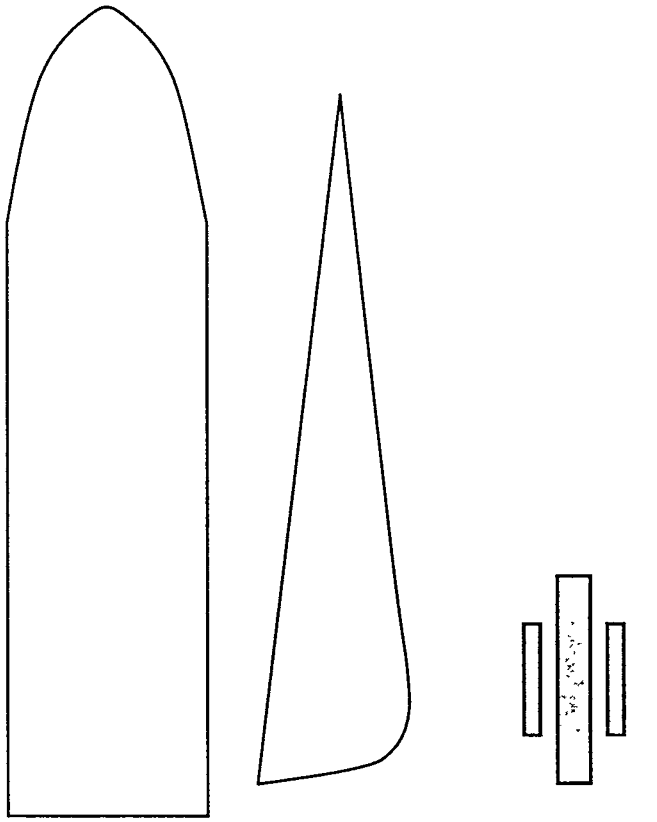


Fig. 8: Size of primary optic and secondary spacecraft relative to Delta IV shroud

packaging consists of cones that enclose both side of the lens and support the weight of the lens. The support enclosure has not been designed and may grow relative to its allocated mass. The propulsion system would use arc-jet technology and have a ten year propellant supply to maneuver the secondary spacecraft for observations. At this stage of design the mass contingency is specified as 100%. The Delta IV-M+5,4 launch vehicle has an approximate payload capacity of 3900kg into an earth trailing orbit. This provides plenty of margin for this design. One cannot use a smaller launch vehicle despite the large mass margin because the configuration is limited by available volume of the shroud rather than the payload mass capacity.

Component	Mass (kg)
Primary (100mm glass)	160
Packaging	200
Secondary & bus	760
Propulsion	350
100% contingency	1470
Total spacecraft	2940

Delta IV-M+5,4 payload capacity to earth trailing orbit is approximately 3900 kg

Table 1: Mass budget for 20m space telescope spacecraft

5. OTHER POTENTIAL APPLICATIONS

5.1 Power Beaming

Large low-mass Fresnel optics can enable power beaming over very long distances. Power beaming to and from geostationary orbits would be possible. Once long distance beaming is possible, then it no longer makes sense to locate the required power supplies and lasers in orbit. Placing these assets on the surface of the Earth will allow much simpler technology, practical maintenance and much lower costs. The laser power can be beamed up to a geostationary station using an Earth-based telescope with a large conventional primary optic and smaller adaptive optics in the optical train.

A satellite in geostationary orbit can capture the laser beam and redirect it to targets of interest using low-mass Fresnel phase plates. The Fresnel lenses will have transmissive efficiencies over 98%. Table 2 gives the typical ranges for several missions and the required lens size. The transmitting lens and the delivered spot size are assumed to be the same, but one can trade one against the other with their product being conserved.

Mission	Range (10^3km)	Visible light spot / optic diameter (m)
geo to leo	40	6
geo to geo	80	9
geo to moon	400	20
geo to L1 / L2	1500	40

Table 2: Power beaming missions and required optic sizes

5.2 Spacecraft communications

For spacecraft communications the low mass and easy tolerances of thin membrane Fresnel optics makes optical communication with large transmitting apertures possible. For spacecraft communications

$$\text{Data rate / spacecraft transmitter power} \sim d^2_{transmitter} D^2_{receiver} / \lambda$$

Table 3 compares potential laser and radio communication systems and show that 1μm lasers may have four or five orders of magnitude advantage in terms of higher data rates or lower power requirements.

	λ(m)	$d_{trans.}$ (m)	$D_{rec.}$(m)	d^2D^2/λ
radio	0.01	1	10	10^4
laser	10^{-6}	10	3	10^9

Table 3: Comparison of laser and radio communication systems

5.3 Solar Sail Mission Impact: Enabling for Fly-by Missions

The low payload capacity of solar sail spacecraft makes the inclusion of very large aperture imaging impossible unless the optics are extremely light. If the solar sail itself forms the primary optic, then very large aperture imaging systems may be possible. The solar sail must be reflective (or absorbing for carbon sails) and very thin. If the sail is used as a reflective optic, then the $\lambda/10$ optical precision requirement in a membrane structure will be extraordinarily difficult or impossible. The use of the sail as a transmissive optic greatly relieves the optical precision requirements, but one cannot make a transmissive Fresnel phase plate from this opaque material. The use of an amplitude zone plate optical design allows the use of reflective or absorbing sail material while still gaining the advantages of a transmissive membrane design. Ref.7 gives an analysis of this mission and discusses an optical demonstration of broadband amplitude zone plate telescope performance.

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